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Report addresses the compatability of the Reliability, Availability and Maintainability (RAM) and Manpower and Personnel Integration (MANPRINT) programs, and suggests some specific ways of integrating their objectives and techniques within the framework of system performance modelling. The report begins with background discussion on RAM and MANPRINT, and proceeds to an overview of some proposed applications of human factors to existing system effectiveness and availability models. One recent MANPRINT approach to RAM analysis is highlighted, in particular. This approach is a proposal developed by Lowry and Seaver for the U.S. Army Research Institute. Using a hypothetical weapon system as an example, the report demonstrates how Lowry and Seaver's methodology can be applied to the operational availability (A_o) model.

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INTEGRATION OF MANPRINT AND RAM:
A MARRIAGE OF MAN AND MACHINE IN SYSTEM PERFORMANCE MODELLING

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Introduction

"Nothing can be wisely prescribed in an army...without exact knowledge of the fundamental instrument, man, and his state of mind, his morale, at the instant of combat."

--Colonel Ardant du Picq, French Army, 1868

The ultimate goal of the Army's materiel acquisition process is to deploy capable, affordable and fully supportable systems that are responsive to validated Army requirements. Realizing this goal has become an increasingly complex and challenging business in recent years due to the combined effect of accelerating technological growth and fixed or diminishing manpower and fiscal resources. Within the U.S. Army, various programs have emerged to meet the challenges of modernization. Among these programs are Reliability, Availability and Maintainability (RAM) and Manpower and Personnel Integration (MANPRINT). Both of these programs are designed to ensure the supportability of fielded systems; yet they have remained chiefly independent in terms of what they do, how they do it, and who participates in the process. This paper addresses the compatibility of the RAM and MANPRINT programs, and suggests some specific ways of integrating their objectives and techniques within the framework of system performance modelling. The methods described are not comprehensive, nor are the findings conclusive. However, the selected studies and methodologies do represent the development of important initiatives to improve RAM planning and analysis through the influence of MANPRINT.

The paper begins (Section 1) with background discussion on RAM and MANPRINT, and proceeds in Section 2 to an overview of proposed applications of human factors to existing system effectiveness and availability models. Section 2 also describes, in some detail, a recent MANPRINT approach to RAM analysis developed by Lowry and Seaver for the U.S. Army Research Institute. In Section 3, a hypothetical system is introduced, and is used to demonstrate how Lowry and Seaver's method can be applied to a mathematical model for operational availability (A_o). The paper concludes with summary findings in Section 4.

Section 1. Background

The process of transforming a materiel concept into an operable and supportable equipment system depends in large part on how well the system characteristics and requirements are defined. At the very beginning of an Army acquisition program, numerous decisions have to be made on what kind of system will be developed, procured or improved. Questions such as, how well must the system perform, how much will it cost, and who will be available to operate and support it, are among the issues that must be resolved in defining system requirements.

The Army RAM program contributes importantly to the decision-making process by defining the reliability, availability and maintainability (RAM) requirements of emerging materiel systems. Consisting of a mix of engineering, accounting and management tasks, RAM is designed to ensure that the materiel systems provided to the Army are operationally ready for use when needed, will successfully perform their assigned functions, and are capable of being economically operated and maintained with the skills and training expected to be available. In short, RAM seeks to deliver reliable and supportable equipment to the operational forces.

The methods used to execute RAM objectives are well documented in TRADOC/AMC Pamphlet 70-11, RAM Rationale Report Handbook. Initial emphasis is placed on determining RAM requirements and on predicting RAM achievement. Typical measures of RAM effectiveness include operational availability, maintenance ratio, mean time between operational mission failure, mean time to repair, and mission reliability; and a well defined set of mathematical tasks exists to establish and allocate the values of these and other RAM parameters.

The product of these accounting tasks is a set of operational RAM measures specifically tailored to a materiel system. These measures describe quantitatively the combined effects of item design, quality, installation, environment, operation, maintenance and repair; and they predict what overall system reliability, availability and maintainability will be when all significant operational elements (e.g., hardware, software, crew, maintenance personnel, etc.) are considered. What these traditional RAM measures fail to show, however, is the amount that each operational element individually contributes to total system performance. Human performance and human error, in particular, are crucial components of the system performance equation, because they contribute so substantially to total system effectiveness. In an analysis of STINGER performance, for example, human failure was estimated to degrade expected system effectiveness by 30 percent. (Reference 2, p. 131.) Traditional RAM methodology, however, tends to obscure the extent and cause of such human performance problems by combining the effects of the operator and maintainer with all other operational factors in the system performance model. When thus aggregated with other operational influences, human performance problems lose their identity and measurability. John Lowry and David Seaver, writing for the U.S. Army Research Institute (ARI), state the problem this way: the models for system effectiveness and availability are sound, but they require modification to directly incorporate soldier performance data. (Reference 6, p. 2.)

The collection, interpretation and application of soldier performance data are the province of the Army's Manpower and Personnel Integration (MANPRINT) program. Recently conceived and institutionalized, the Army MANPRINT initiative seeks to improve total system performance by continuously integrating human factors engineering, manpower, personnel, training, system safety and health hazard considerations throughout the materiel development and acquisition process. In other words, MANPRINT is a process for optimizing the relationship between the hardware/software and human contribution to system performance. (Reference 5, p. 1.)

Among the resources available to the MANPRINT program are several important bodies of knowledge, incorporating studies, analyses, and basic and applied research in the areas of human factors engineering, system safety, biomedicine, and behavioral psychology. The data bases and methodologies integrated by MANPRINT serve two important purposes. First, they provide the means for calculating how soldier performance affects system performance; and, second, they enable system designers to identify, diagnose and suggest fixes for soldier performance deficiencies.

MANPRINT accomplishes its objectives through a comprehensive management and technical program built into the weapon system Life Cycle Management Model (LCSMM). The emphasis in this program is on influencing system design; therefore, the bulk of MANPRINT activity occurs early in the development cycle when design changes are easier and less costly to make. During the concept exploration (research and tech-base activities) phase, materiel and combat developers formulate system-specific MANPRINT goals and constraints, and incorporate them into planning and contractual documents, such as the Operational and Organization (O&O) plan and initial concept contracts. Specific MANPRINT products like the Early Comparability Analysis (ECA) and HARDMAN analysis are used in this phase to assist in identifying goals and constraints, and to evaluate the feasibility of competing concepts from a MANPRINT perspective. Design prototypes are evaluated next for MANPRINT acceptability during the demonstration and validation phase (proof of principle); and, in the full-scale development (development and production prove-out) phase, technical and operational tests are reviewed in order to assure that MANPRINT issues and criteria are adequately tested and evaluated. During the final acquisition stages (production-deployment), MANPRINT assesses the ability of the Army force structure to man and support the fielded system. AR 602-2, the

Army regulation governing MANPRINT in the materiel acquisition process, sums up these life cycle activities this way:

> "The philosophy of the MANPRINT Program is to have the Army and industry take necessary actions to answer the question: Can this soldier with this training perform these tasks to these standards under these conditions? (Ref. 11, p. 3)

Where the RAM and MANPRINT programs converge is in their interest in the supportability of Army weapon systems, and in their application of quantitative techniques to the evaluation of overall system performance. There is also some overlap in the make-up of the organizations charged with executing the two programs. Within combat development communities, for instance, MANPRINT and RAM responsibilities are often both vested in the logistics organization. Given this interdependence, and given also the scope and magnitude of the Army modernization program, the merger of RAM and MANPRINT methodology would seem to be a natural and necessary evolutionary development. Indeed, in the last decade and a half, considerable research and analysis has been dedicated to incorporating human performance data into system performance models. Succeeding sections of this paper describe some of those early research efforts, and highlight one recent proposal for applying MANPRINT methodology to RAM.

Section 2. Applications of Human Factors to System Performance Models

DARCOM Pam 706-102, Engineering Design Handbook Army Weapon Systems Analysis, Part Two, provides the official framework for human factors applications in weapon systems analysis. Chapter 33, Introduction to Human Factors and Weapon Systems Analysis Interface Problems, in particular, addresses the man-machine interface and states that in order to evaluate weapon systems properly, we must know accurately what human performance contributes to system effectiveness. Quoting John Weisz, Director, U.S. Army Human Engineering Laboratory (HEL), from a paper he wrote in 1976, the pamphlet cites a growing body of literature and the development of methodologies which, "if properly utilized, will materially assist system analysts in conducting their analyses throughout the life cycle of a weapons system." (Reference 13, p. 33-2.) The goal, indeed the imperative, according to Weisz, is to include man's contributions to the system each and every time system performance, system effectiveness, system dependability, system reliability, system capability, and cost effectiveness are considered.

The message to be drawn from this literature is in two parts: (1) human factors considerations are essential to analyses of the potential effectiveness of weapon systems; and (2) proponents of human factors engineering have recognized the importance of the human element for some time, and have developed methods for determining and expressing quantitatively man's contribution to system performance. Among the work produced since the early 1970's on human factors and weapon system analysis interface are several studies undertaken by or for HEL, ARI and the Department of the Navy. Taken in order of publication (and described in greater detail below), these works include:

a. A 1972 study contracted by HEL on the incorporation of human performance reliability data in the system reliability models for an Army machine gun. (Reference 7)

b. A 1974 study conducted by HEL comparing the effects of human performance and human error on the system performance of two different equipment designs for a TACFIRE message entry device. (Reference 4)

c. A 1974 study conducted by HEL measuring the frequency and effect of human error in the operation and maintenance of the Stoner rifle and machinegun. (Reference 8)

d. A 1976 report sponsored by the Naval Sea Systems Command on the necessity of obtaining accurate measurements of operational availability, and of identifying the human contribution to equipment failure, equipment downtime and operational availability. (Reference 3)

e. A 1976 guide developed for HEL describing how to obtain, analyze, report and use human performance data in a materiel development program. (Reference 1)

f. A 1986 handbook and report contracted by ARI on a methodology for relating soldier performance to system performance. (Reference 5)

The following paragraphs survey each of these works, and provide an overview of the origins and development of human factors applications to weapons system analysis. Special attention is given to the handbook referenced in paragraph f, above, that incorporates specific MANPRINT concepts and principles in its proposal for integrating soldier performance in system performance models.

One of the earlier works on human reliability and system development (para a, above) is a study authored by J. P. McCalpin for HEL, entitled "Incorporating Human Performance Reliability Data in System Reliability Models." Published in 1972, this study was designed to determine the minimum requirements for a human performance reliability program that would provide data for system reliability models. McCalpin began his work by reviewing the system reliability models used in Army weapon system developments. He found that many of these models consider only equipment failure rates, and operate on the assumption that any failures contributed by man will be reflected in equipment failure rates. The problem with this assessment of reliability, according to McCalpin, is that human errors wind up being "treated at the component level, and that rather complex interfaces which can result in modern weapon systems are not adequately treated." (Reference 7, p. 2.) The solution McCalpin proposed is to include human error data in system reliability models. To prove that this is possible, he selected two system reliability models for predicting the reliability of an Army machine gun, and he showed how the existing mathematical framework could be used to integrate equipment and human performance reliability into predictions of system reliability and maintainability. The next logical step in McCalpin's solution is to develop the requisite human reliability data. McCalpin reviewed the state of the art in human performance reliability research, and concluded that a standardized vehicle for collecting, analyzing and storing human error data can and must be developed.

A second, slightly later study completed by HEL in 1974 (para b, above) addresses specifically the collection and evaluation of human error data. Published as Technical Memorandum 2-74, Human Engineering Evaluation of Two Fixed Format Message-Entry Devices, this study describes an experiment that tested the learning rates and error rates of operators of two different fixed-format message-entry devices (FFMED's) for the TACFIRE system. What the experiment illustrated is that system effectiveness is heavily dependent on operator effectiveness. In the case of the two FFMED's tested, high operator error rates prevented either device from achieving its time or accuracy performance requirements. The experiment further demonstrated that operator error is influenced by individual skills and training. These outcomes substantiate McCalpin's earlier work (preceeding paragraph), and establish that: (1) human performance and human error can be tested, measured and related to system performance; and (2) human performance is critical to achieving system performance requirements.

Similar findings are reported in a second study undertaken by HEL (para c, above). Published in 1974 in Technical Memorandum 22-74, Determining Human Performance Reliability with Infantry Weapons: Part One, this study describes an experiment for measuring the extent and consequence of human error in the operation and maintenance of the Stoner rifle and machinegun. HEL designed the experiment to collect error data on trained troops in a field test. Through direct observation of operator performance, HEL acquired empirical human error data and showed how that data could be translated into human error rates and estimations of the probability of human error. When added to the hardware failure rates, these operator failure rates enabled HEL to apply human reliability directly to the weapon system reliability models. These findings demonstrated that earlier hypotheses by McCalpin and others are correct: human performance is a significant factor in system performance, and it can be included in system performance models.

A study commissioned by the Naval Sea Systems Command (para d, above) also addresses the contribution of the human element to equipment failure. Entitled "Naval Sea Systems Operational Availability Quantification and Enhancement," the 1976 technical report documents a Navy effort to improve the specification and demonstration of shipboard reliability and maintainability. Principal investigator for the study was H. B. Lipsett, Naval Underwater Systems Center. Working in conjunction with E. F. Howard, Lipsett examined conventional measurements of operational availability (A_o), and determined that there is inadequate identification of the impact of human performance on equipment failure, equipment downtime and operational availability. To be precise, the study estimated that fifty to seventy percent of all failures of major weapon and space systems are caused by human initiated malfunctions, yet human failure is usually misdiagnosed as design error, component unreliability, or some other hardware problem. (Reference 3, p. 7.) The consequence of this oversight, according to Howard and Lipsett, is that system developers tend to treat the symptoms of system failure rather than the causes, and they subsequently fail to produce any real improvement in A_o. As had previous investigators, Howard and Lipsett concluded that there is an urgent need for a method of quantifying and measuring human performance, and for modifying present models of reliability and maintainability to ensure that they reflect human-centered, as well as hardware-centered problems in man/machine systems.

In 1976, HEL published a "Guide for Obtaining and Analyzing Human Performance Data in a Material Development Project" (para e, above). This guide addresses the human factors data requirements articulated by earlier studies (see preceeding paragraphs, this section), and prescribes standardized methods for acquiring and using these data in a materiel development program. To illustrate their approach, HEL describes two human factors engineering (HFE) tests. One test is of the mission control station of Compass COPE; and the other is of the Communication Control Unit (CCU) for TACFIRE. Using these tests as examples, the guide establishes the importance of measuring and predicting human performance error. The guide also specifically addresses the application of human error data to A_o, and finds that the full contribution of human performance to operational availability cannot be adequately assessed unless the actual number of human errors measured during an HFE test is compared with the opportunities for error, and that ratio is used in the reliability component of the A_o equation. (Reference 1, pp. 43-44.) Echoing earlier studies, the guide concludes that human reliability predictions must be developed and combined with hardware failure estimates to produce accurate measures of overall system performance.

In keeping with the conclusions and recommendations of these early studies, John Lowry and David Seaver published a handbook for ARI in 1986 entitled, "Handbook of Quantitative Analysis of MANPRINT Considerations in Army Systems" (para 4, above). One of the most up to date and, for the purposes of this paper, important works on human/system performance, this handbook proposes a comprehensive, step-by-step procedure for relating soldier performance to system performance. The central premise of this work and that of its predecessors is basically identical; that is, soldier performance is an integral component of a system's ability to accomplish its required missions. Unlike the earlier works, however, Lowry and Seaver's approach infuses MANPRINT-specific concepts and procedure into its recommended techniques for integrating soldier and equipment performance.

In defining the role of MANPRINT in system performance, Lowry and Seaver review traditional methodologies for evaluating human factors, safety and mission performance. They find that, while these domains are individually well defined, the contribution that each makes to the other is largely unknown and unmeasured. System effectiveness and system availability, for example, are the two primary measures of system performance, yet neither explicitly measures soldier erformance, nor permits soldier performance to be distinguished from equipment performance. The solution to this gap in soldier-system analysis, according to Lowry and Seaver, is to modify the traditional models so that they include soldier performance data.

In implementing their sol[illegible], Lowry and Seaver propose a six-step procedure that incorporates a mix of systems analysis modeling techniques and algorithms, human performance measurement and evaluation, statistics, field operations, and test and evaluation. Figure 2-1, from Lowry and Seaver's technical report (reference 6, p. 9), depicts the sequence of steps involved in this procedure. Central to the process, which is described as continuous, is the development and application of quantitative models for MANPRINT system performance.

The models that Lowry and Seaver propose be used are a modified version of two standard RAM measures of effectiveness (MOE's): reliability and operational availability. Redesignating these as MANPRINT effectiveness and MANPRINT availability, respectively, Lowry and Seaver show how the traditional RAM models can be decomposed and recreated to include the probability of operator and maintainer error and other soldier related effects. Their equation for MANPRINT availability (A_m), in particular, is reproduced at Figure 2-2, above the standard equation for operational availability from AR 702-3. (Reference 5, p. 16, and reference 12, Glossary 1.) As a comparison of these equations shows, Lowry and Seaver's derivation of A_m refines the definition of standby time (and, therefore, of uptime) by distinguishing between operable standby time and inoperable standby time. The latter occurs, according to Lowry and Seaver, when maintenance

MANPRINT CONTINUOUS AND COMPREHENSIVE EVALUATION

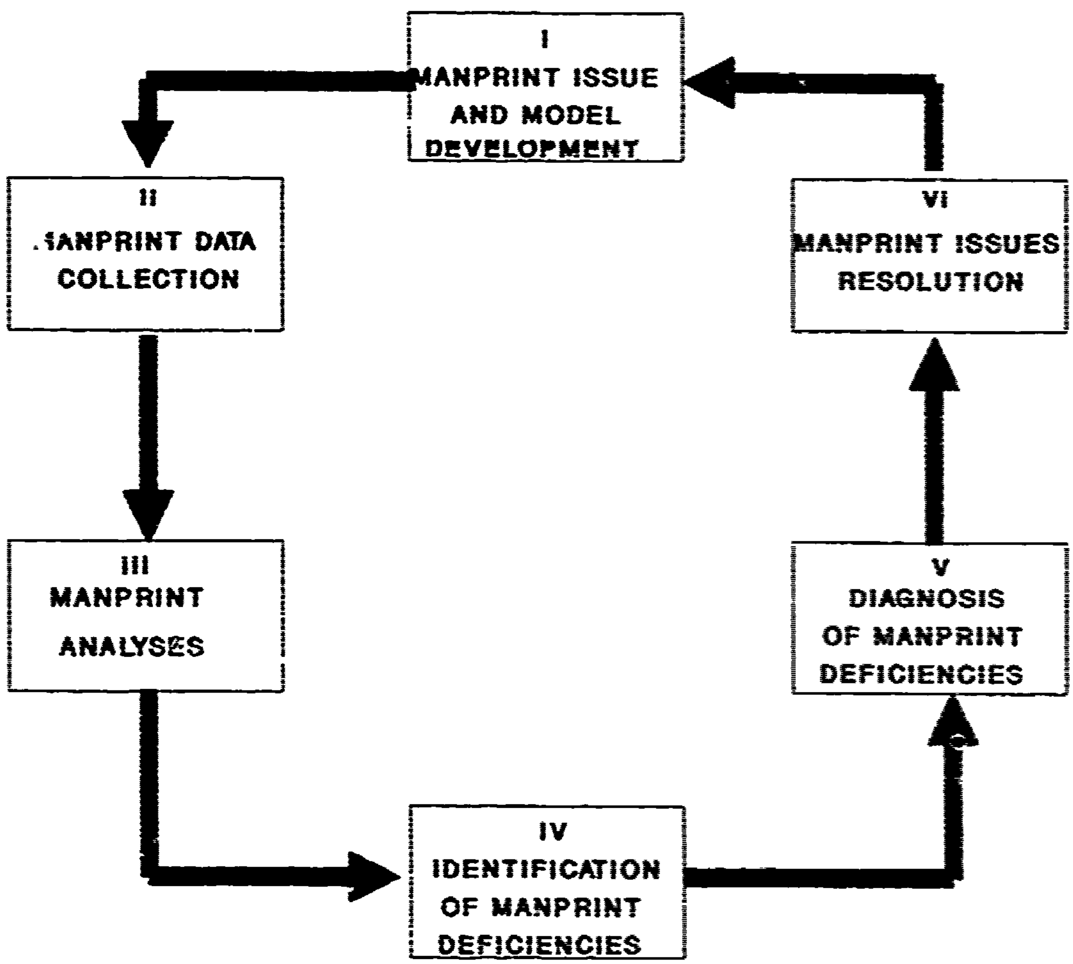

Figure 2-1

AVAILABILITY EQUATIONS

MANPRINT AVAILABILITY EQUATION (LOWRY & SEAVER)

$$Am = \frac{OT + STo}{OT + STo + STi + TCM + TPM + TALDT}$$

Where:

OT	=	Operating time
STo	=	Operable standby time
STi	=	Inoperable standby time
TCM	=	Total corrective maintenance time
TPM	=	Total preventive maintenance time
TALDT	=	Total administrative and logistics downtime

TRADITIONAL OPERATIONAL AVAILABILITY EQUATION (AR 702-3)

$$Ao = \frac{OT + ST}{OT + ST + TCM + TPM + TALDT}$$

Where:

OT	=	Operating time
ST	=	Standby time
TCM	=	Total corrective maintenance downtime
TPM	=	Total preventive maintenance downtime
TALDT	=	Total administrative and logistics downtime

Figure 2-2. Equations for Measuring Availability

personnel fail to restore equipment to an operable condition, but are unaware that they have failed. In other words, during inoperable standby time, a system is presumed to be up when, in fact, it is down. Because of the major role that soldier performance plays in maintenance time and accuracy, Lowry and Seaver maintain that their version of the availability model measures system availability more precisely. (Clearly, there are other RAM components, such as administrative and logistics downtime, that might also benefit from the application of soldier performance data, and that Lowry and Seaver do not treat.)

The data required for the MANPRINT availability and effectiveness models are outlined at Figure 2-3. (Reference 5, p. 2.) Since RAM and MANPRINT data requirements overlap, Lowry and Seaver propose that common data requirements be identified, and data collection efforts be integrated in order to conserve the Army's test and evaluation resources. Their aim is to establish a continuous flow of information that supports MANPRINT system analysis fully, but does not add appreciably to test and evaluation workloads. Paraphrasing the standard MANPRINT slogan quoted earlier, Lowry and Seaver summarize their data requirements as representing the information and techniques necessary to answer the question:

> "How well does the manned system achieve its intended mission requirements given its current level of maturity?" (Reference 6, p. 37.)

In Section 3, following, a hypothetical system is used to show how Lowry and Seaver's technique modifies traditional RAM methodology.

Section 3. MANPRINT Availability of a Sample System

The RAM Rationale Report Handbook, TRADOC/AMC Pam 70-11, introduces a hypothetical system, denoted XYZ, to illustrate standard RAM methodology. (Reference 15.) In this section, the same system (XYZ) is reintroduced to show how Lowry and Seaver's approach modifies traditional methodology, specifically the derivations of availability.

Chapter 2 of the RAM Handbook describes system XYZ as an air defense/ground defense system with a rapid fire cannon and a target acquisition radar. According to the operational mode summary/mission profile (OMS/MP) invented for the system, XYZ has seven major missions in peacetime and five major tasks. The peacetime OMS/MP tables from the handbook (Figure 3-1) identify these missions and tasks specifically (reference 15, p. 2-6). Total operating time and alert time for the system (column f) is 409 hours in peacetime, and total calendar time is 496 hours. Using these data, the handbook shows how we derive a value of A_o

MANPRINT DATA

- MANPRINT Effectiveness (Em)
  - Operator performance probability on critical soldier tasks (specified through prior analysis)
  - System performance probability on critical system functions (specified through prior analysis)
  - Human factors data on system operations (e.g., critical incidents, observations, surveys, interviews, etc.)

- MANPRINT Availability (Am)
  - Mean corrective maintenance time
    - --Mean preparation time
    - --Mean fault location time
    - --Mean item obtainment time
    - --Mean fault correction time
    - --Mean adjustment/calibration time
    - --Mean checkout time
    - --Mean cleanup time
  - Probability of correct maintenance
  - Mean preventive maintenance time
  - System/equipment reliability data
  - Human factors data on maintenance activities (e.g., critical incidents, observations, surveys, etc.)

- Personnel Characteristics of Test Participants
  - Aptitude (e.g., ASVAB scores)
  - Training (e.g., SQT scores)
  - Physical characteristics (e.g., PULHES)

Figure 2-3. MANPRINT Measurement Requirements

Table 2-3. Peacetime OMS for the XYZ System

Mission	(a) OT	(b) OT + AT	(c) CT	(d) Number of Missions	(a) x (d) = (e) Total OT	(b) x (d) = (f) Total OT + AT	(c) x (d) = (g) Total CT
1. ARTEP	9.05 Hrs	11 Hrs	11 Hrs	3	27 Hr	33 Hr	33 Hr
2. Division Level Readiness Exercise	2.0	5	6	7	14	35	42
3. Battalion Level Readiness Exercise	1.0	4	4	6	6	24	24
4. Platoon/Battery Level Readiness Exercise	.4	1	1	39	16	39	39
5. Fld Training Exercise Spt	1.4	4	4	37	52	148	148
6. ARTEP Support	9.05	11	11	6	54	66	66
7. Local Training Area	15	32	72	2	30	64	144
Total Scenario	XX	XX	XX	100	199	409	495

Table 2-4. MP for the XYZ System ARTEP Mission

ARTEP MISSION TASKS	NUMBER OF OCCURRENCES	OPERATING TIME FOR EACH TASK	TOTAL OPERATING TIME
Search & Surveillance	18	20 min	6.00 hrs
Acquisition	9	15 min	2.25 hrs
Track	4	5 min	.33 hr
Fire (Air)	2	2 min	.07 hr
Fire (Ground)	3	8 min	.40 hr
Total	XX	XX	9.05 hrs

Figure 3-1. Operational Mode Summary/Mission Profile

that will satisfy mission requirements. That value is represented by the equation:

$$A_o = \frac{OT + AT}{CT} = \frac{409}{496} = .82$$

Where OT = Operating time
AT = Alert time
CT = Calendar time

The resulting A_o requirement of 0.82 expresses the minimum availability necessary to enable system XYZ to accomplish all missions identified in the OMS/MP. What this assessment does not measure, however, is the availability that can actually be expected to result when the system is used in a typical maintenance and supply environment. That availability is traditionally represented by the formula (see also Figure 2-2):

$$A_o = \frac{OT + ST}{OT + ST + TCM + TPM + TALDT}$$

Where OT = Operating time
ST = Standby time
TCM = Total corrective maintenance downtime
TPM = Total preventive maintenance downtime
TALDT = Total administrative and logistics downtime

The flaw in this formula, however, is that it does not account for variations in soldier performance of corrective and preventive maintenance tasks. In other words, the standard formula assumes that all standby time is uptime, and that maintenance personnel never err when they report that the system is operable.

Clearly, however, soldiers do err in their performance of maintenance tasks, and this error does contribute to downtime for the system. In order to measure the impact on system availability, the contribution of human error must be quantified and included in the assessments of downtime. Lowry and Seaver's formula for accomplishing this is a modified operational availability equation that they label "MANPRINT Availability" (A_m) (see also Figure 2-2):

$$A_m = \frac{OT + ST_o}{OT + ST_o + ST_i + TCM + TPM + TALDT}$$

Where OT = Operating time
ST_o = Operable standby time
ST_i = Inoperable standby time
TCM = Total corrective maintenance downtime
TPM = Total preventive maintenance downtime
TALDT = Total administrative and logistics downtime

While this formula resembles the traditional availability equation (previous page), it differs significantly from the other in its treatment of maintenance downtime. The most obvious difference in Lowry and Seaver's formula is that it introduces two expressions for standby time instead of just one. These two expressions are operable standby time (ST_{o}) and inoperable standby time (ST_{i}), and they are used to distinguish between cases of successful maintenance and unsuccessful maintenance, respectively. Second, the formula includes in its values for corrective and preventive maintenance the contributions of human factors, safety, training and health hazards to system downtime. And, third, the formula invokes a systematic procedure for acquiring and relating soldier performance data to each critical item of equipment, each failure type/mode, and each maintenance task. Using system XYZ as an example, their approach follows these steps:

The first step is determining how much time is spent on maintenance tasks, and how successfully the equipment operates following maintenance. Figures 3-2 through 3-7 display these hypothetical data for system XYZ, using Lowry and Seaver's proposed worksheet formats (reference 5, Appendix B, H, I, C, J, and K.)* Separate worksheets are designed to be used to record the performance of individual maintenance personnel for each maintenance occurrence (Figures 3-2 and 3-5). These results, in turn, are summarized for the individual soldier (Figures 3-3 and 3-6) and for the system as a whole (Figures 3-4 and 3-7) on each critical item of equipment. For system XYZ, critical items include the essential components of the tracked chassis, the 20mm cannon, the sight, the mount, and the radar set. (For the sake of simplicity, only the radar set is examined in this illustration.)

Next, the summary data from these worksheets are accumulated for all critical items of equipment in system XYZ, and the resulting totals are transferred to the system TCM and TPM worksheets at Figures 3-8 and 3-9, respectively. (Reference 5, Appendix L and M.) Completion times in minutes are obtained directly from the summary worksheets for each critical item of equipment (Figures 3-4 and 3-7); and the failure rates, "F_{ij}", are derived from RAM data. The sum of the products of these completion times and failure rates yields the total maintenance time for corrective maintenance (Figure 3-8) and preventive maintenance (Figure 3-9).

The last essential step in deriving MANPRINT availability is calculating operable and inoperable standby time (Figure 3-10). This calculation is accomplished through a series of intermediate steps outlined in subparagraphs a through g, following. (Reference 5, pp. 24-25.)

*Note: The social security numbers in these examples are fabricated. The combination of actual names and social security numbers should be treated in acordance with the Privacy Act.

CORRECTIVE MAINTENANCE PERFORMANCE WORKSHEET

I. ADMINISTPATION

1. Test Participant: SGT Karl V. Clausewitz, #012
2. Social Security Number: 228-25-1831
3. a. Equipment Item: Radar Receiver - Transmitter (2)
   b. Failure Mode: Power Supply
   c. Conditions: Operational test, daytime, field conditions, inclement weather, MOPP Ø
4. Data Source: UT I
5. Data Collector/Observer: H. Fosdick, #001
6. Date: 18 APR 88   7. Time: 1435 hrs.

II. PERFORMANCE

1. PREPARATION	TIME:* 0.09 hrs
2. FAULT LOCATION	TIME: 0.35
3. ITEM OBTAINMENT	TIME: 0.25
4. FAULT CORRECTION	TIME: 0.6
5. ADJUSTMENT/CALIBRATION	TIME: N/A
6. CHECKOUT	TIME: 0.08
7. CLEANUP	TIME: 0.12

Does the equipment operate after maintenance? YES X NO ___

III. PERFORMANCE DESCRIPTION

Repairman removed and replaced faulty power supply assy without difficulty. Repair required removal and reinstallation of rcvr-transmitter on mount.

*Use NA when task is not performed.

Figure 3-2

SUMMARY OF CORRECTIVE MAINTENANCE FOR INDIVIDUAL SOLDIER

I. ADMINISTRATION

1. Test Participant: SGT Karl V. Clausewitz, #012
2. Social Security Number: 228-25-1831
3. a. Equipment Item: Radar Receiver-Transmitter (2)
   b. Failure Mode: Power Supply
   c. Conditions: Operational test, daytime, field conditions, MOPP 0

II. PERFORMANCE

A.

	Number of Trials	Average Time
1. PREPARATION	3	0.08 hrs
2. FAULT LOCATION	3	0.33
3. ITEM OBTAINMENT	3	1.05
4. FAULT CORRECTION	3	0.60
5. ADJUSTMENT/CALIBRATION	NA	—
6. CHECKOUT	3	0.08
7. CLEANUP	3	0.10

B.

1. Number of Maintenance Performances: 3
2. Number of Times Equipment Operated After Maintenance: 3
3. % Successes: 100

Figure 3-3

SUMMARY OF CORRECTIVE MAINTENANCE FOR SYSTEM AVAILABILITY

I. ADMINISTRATION

1. Equipment Item: Radar Rcvr-Transmitter (2)
2. Failure Mode: Power Supply
3. Conditions: Operational test, daytime, field conditions MOPP Ø

II. PERFORMANCE

A.

	Average Time
1. PREPARATION	0.09 hrs
2. FAULT LOCATION	0.35
3. ITEM OBTAINMENT	0.75
4. FAULT CORRECTION	0.55
5. ADJUSTMENT/CALIBRATION	NA
6. CHECKOUT	0.09
7. CLEANUP	0.17

B. AVERAGE % SUCCESS OF EQUIPMENT OPERATION AFTER MAINTENANCE 95%

Figure 3-4

PREVENTIVE MAINTENANCE PERFORMANCE WORKSHEET

I. ADMINISTRATION

1. Test Participant: PFC Tony Stradivari, #008
2. Social Security Number: 205-69-1641
3. a. Equipment: Radar Receiver-Transmitter (2)
   b. Type of Maintenance: Clean air filter
   c. Conditions: Operational test, daytime field conditions, inclement weather, MOPP Ø
4. Data Source: UTI
5. Data Collector/Observer: H. Fosdick, #001
6. Date: 18 APR 88 7. Time: 0730 hrs

II. PERFORMANCE

1. MAINTENANCE COMPLETION TIME: 0,08 hrs
2. Does the equipment operate after maintenance? YES X NO____

III. PERFORMANCE DESCRIPTION

Page of instructions on cleaning air filter missing from TM. Air filter appeared excessively dirty when removed: indication that PM not being performed often enough.

Figure 3-5

SUMMARY OF PREVENTIVE MAINTENANCE FOR INDIVIDUAL SOLDIER

I. ADMINISTRATION:

1. Test Participant: PFC Tony Stradivari, # 008
2. Social Security Number: 205-69-1641
3. a. Equipment Item: Radar Receiver-Transmitter (2)
   b. Type of Maintenance: Clean air filter
   c. Conditions: Operational test, daytime field conditions, MOPP 0

II. PERFORMANCE

1. Number of Trials: 10
2. Average Maintenance Completion Time: 0.11
3. Number of Times Equipment Operates After Maintenance: 10
4. % Successes: 100

Figure 3-6

SUMMARY OF PREVENTIVE MAINTENANCE FOR SYSTEM AVAILABILTY

I. ADMINISTRATION

1. Equipment Item: Radar Receiver – Transmitter (2)
2. Type of Maintenance: Clean air filter
3. Conditions: Operational test, daytime, field conditions, MOPP 4

II. PERFORMANCE

1. AVERAGE PREVENTIVE MAINTENANCE COMPLETION TIME: 0.17
2. AVERAGE % SUCCESS OF EQUIPMENT OPERATION AFTER MAINTENANCE: 98%

Figure 3-7

TOTAL CORRECTIVE MAINTENANCE (TCM) TIME WORKSHEET

CRITICAL EQUIPMENT (I)	FAILURE MODE (J)	MINUTES PT	FLT	IOT	FCT	ACT	CT	CUT	HOURS CMIJ	FIJ	(FIJ)(CMIJ)	TCMI
Antenna Assy	Waveguides	7.20	3.25	10.23	16.20	NA	6.00	7.80	0.84	10	8.40	
	Rotary joints	7.80	3.33	12.40	17.40	NA	6.00	7.80	0.91	5	4.55	
	Reflector/feed	16.80	34.50	8.75	56.40	NA	10.18	9.00	2.26	6	13.56	
	Traverse servo	24.00	30.50	15.84	60.40	36.00	26.20	20.10	3.55	12	42.60	69.11
Rcvr-Trans	Power Supply	5.40	21.00	45.00	33.00	NA	5.40	10.20	2.00	4	8.00	
	Microwave Chass	24.50	96.00	14.83	130.50	NA	28.80	20.00	5.24	3	15.72	
	Pulse Shaper	11.85	20.60	7.17	102.50	NA	7.20	10.80	2.67	7	18.69	
	Coupler	6.00	2.50	4.25	12.00	NA	5.40	6.60	0.61	2	1.22	43.63
Radar Rcvr	Worn gaskets	18.00	3.00	3.89	30.00	NA	8.40	9.00	1.20	5	6.00	6.00
Range Computer	Circuit cards	10.00	36.80	10.90	108.40	18.00	23.60	19.00	3.95	7	27.65	
	Clock assy	6.40	12.80	35.46	23.40	NA	29.00	13.50	2.01	2	4.02	
	Plate assy	7.00	23.00	10.23	21.60	NA	28.20	12.50	1.71	1	1.71	33.38
Pwr Supply	Filters/gaskets	6.60	5.40	2.95	12.00	NA	5.40	6.60	0.65	10	6.50	
	Servo	10.80	7.11	8.93	36.60	NA	12.50	8.00	1.40	11	15.40	
	Converter	12.40	58.60	9.42	102.00	18.00	27.50	11.50	3.99	4	15.96	37.86
Distribution Box	Switches	41.50	42.00	11.31	57.50	NA	22.40	12.00	3.11	9	27.99	
	Boots	36.00	54.50	11.20	60.60	NA	27.50	15.00	3.41	3	10.23	
	Diodes	33.20	52.20	10.38	52.80	NA	23.60	11.80	3.07	2	6.14	44.36

TCM= 234.34

PT=Preparation Time
FLT=Fault Location Time
IOT=Item Obtainment Time
FCT=Fault Correction Time
ACT=Adjustment Calibration Time

CT=Checkout Time
CUT=Cleanup Time

Figure 3-8

TOTAL PREVENTIVE MAINTENANCE (TPM) TIME WORKSHEET

TYPE OF MAINTENANCE (k)	PMT (hours)	RATE (r) (per year)	(PMT)(r)
Interconnecting Cables	0.15	52	7.80
Antenna			
Reflector	0.28	52	14.56
Radome	0.23	52	11.96
Bracket/clamps	0.22	52	11.44
Waveguides	0.18	52	9.36
Covers	0.12	52	6.24
Couplings	0.13	52	6.76
Rcvr-Trans			
Wires/cables	0.15	52	7.80
Tuning tool	0.16	52	8.32
Crystals	0.20	52	10.40
Air filter	0.17	52	8.84
Rcvr Range Computer Air filter	0.18	52	9.36
Power Supply	0.12	52	6.24

PMT=Preventive Maintenance Time

TPM= 119.08 hrs/yr

Figure 3-9

STANDBY TIME (ST) WORKSHEET

TYPE OF MAINTENANCE				
CORRECTIVE				
CRITICAL EQUIPMENT	FAILURE MODE	Pm	RATE (per year)	PRODUCT (Pm x Rate)
Antenna Assy	Waveguides	0.095	10	0.950
	Rotary joints	0.028	5	0.140
	Reflector/Feed	0.101	6	0.606
	Traverse servo	0.094	12	1.128
Rcvr-Trans	Power supply	0.050	4	0.200
	Microwave chassis	0.090	3	0.270
	Pulse shaper	0.126	7	0.882
	Coupler	0.015	2	0.030
Radar Rcvr	Worn gaskets	0.028	5	0.140
Range Computer	Circuit cards	0.120	7	0.840
	Clock assy	0.036	2	0.072
	Plate assy	0.019	1	0.019
Power Supply	Filters/gaskets	0.042	10	0.420
	Servo	0.105	11	1.155
	Converter	0.080	4	0.320
Distribution Box	Switches	0.075	9	0.675
	Boots	0.024	3	0.072
	Diodes	0.090	2	0.180
PREVENTIVE		0.035	52	1.82

Pm = 0.064
OVERALL ST = 3666
ST_I = 235
STo = 3431

Figure 3-10

a. Total standby time (ST) is derived first, either by measuring ST directly during testing, or by calculating it as the difference between total time and the sum of OT, TCM, TPM and TALDT. For system XYZ, ST is calculated as follows. Total calendar time (TT) is 8760 hours (24 hours times 365 days). Operating time (OT) is 40.12 percent of TT, according to the ratio of total OT to CT in the peacetime operational mode summary (Figure 3-1); result: 3515 hours. TCM and TPM are calculated as described in the previous steps, and are equal to 234 hours (Figure 3-8) and 119 hours (Figure 3-9), respectively. Total administrative and logistics downtime (TALDT) is estimated using a decision tree analysis, which yields an average ALDT of 136 hours per operational mission failure for support alternative 1 (reference 15, p. 6-23). Combining the ALDT estimate with the OT of 3515 hours and the mean time between operational mission failure (MTBOMF) of 390 hours (minimum acceptable value) from the RAM Rationale Report Handbook (reference 15, p. 6-53) gives a TALDT estimate of 1226 hours. ST, then, equals: TT − (OT + TCM + TPM + TALDT), or 8760 − (3515 + 234 + 119 + 1226) = 3666 hours.

b. The probability of maintenance failure (P_m) is calculated next, using the soldier performance data collected and recorded on the maintenance summary worksheets for system availability (Figures 3-4 and 3-7). These worksheets provide the average percent of successful equipment operation following maintenance, as observed by a data collector. In some cases, empirical data may not be available (for example, because of system immaturity). In such cases, expert judgment can be used to produce the needed performance estimates. The recommended expert judgment procedure, according to Lowry and Seaver, is a psychological scaling technique for assigning the likelihood of human success on a probability scale or on the time to complete a task.

c. Rate is defined as the frequency of maintenance, and it is calculated for each failure mode of each critical item of equipment. Both corrective and preventive maintenance rates are established by measuring the number of times the given type of maintenance is performed in a given time period. In this example, the rates for corrective maintenance are for a total time of one year, or 8760 hours, and the values are taken from the TCM worksheet (Figure 3-8, column "F_{ij}"). The preventive maintenance rate is once every week, or 52 times per year.

d. The product of the rates and the maintenance failure probabilities is calculated by multiplying P_m and rate for each failure mode of each critical item of equipment. The results for system XYZ are displayed in the last column of Figure 3-10, Standby Time (ST) Worksheet.

e. The overall maintenance failure probability for the system is calculated in three steps. First, the rates for each critical item and each failure mode (para c, above) are summed to give a system total; result: 155. Second, the products of the rates and maintenance failure probabilities are summed for all failure modes and all critical items; result: 9.919. And, last, the overall maintenance failure probability is calculated by dividing the sum of the rates into the sum of the products; result: 0.064.

f. Following steps a through e, above, inoperable standby time (ST_i) is calculated by multiplying total standby time (para a) by the overall maintenance failure probability (para e). The outcome for system XYZ is (3666)(0.064) = 235 hours.

g. Operable standby time (ST_o) is the difference between total standby time (para a, above) and inoperable standby time (para f, above). The calculation for ST_o is: ST multiplied by one minus the overall maintenance failure probability (para e, above), which, for system XYZ, equals 3666 x (1 - 0.064) = 3431 hours.

Once the foregoing steps are accomplished, the MANPRINT availability formula can be completed for the system under study, in this case, system XYZ. Repeated below is Lowry and Seaver's basic formula for A_m, and, below that, the same formula with the values entered for system XYZ. As shown, MANPRINT availability for system XYZ equals 0.79.

$$A_m = \frac{OT + ST_o}{OT + ST_o + ST_i + TCM + TPM + TALDT}$$

$$= \frac{3515 + 3431}{3515 + 3431 + 235 + 234 + 119 + 1226}$$

$$= 0.79$$

This compares with an operational availability of 0.82 derived using the traditional formula shown below.

$$A_o = \frac{OT + ST}{OT + ST + TCM + TPM + TALDT}$$

$$\frac{3515 + 3666}{3515 + 3666 + 234 + 119 + 1226}$$

$$= 0.82$$

The difference between the two availability estimates of A_o and A_m, though small in this example, demonstrates that human error does have an impact on maintenance and, correspondingly, on system performance. For system XYZ, the contribution of soldier performance during maintenance reduces system availability below the minimum acceptable value of 0.82. Human reliability, therefore, can be an important factor in determining whether a system can meet its mission accomplishment requirements and deliver the requisite equipment readiness.

Section 4. Summary

As stated in the introduction to this paper, the chief business of the materiel acquisition process is to ensure that the weapon systems provided to the Army are fully capable, affordable, supportable and responsive to validated Army requirements. Both RAM and MANPRINT contribute importantly to this goal. RAM provides a set of engineering, accounting and management tasks for ensuring that materiel systems will successfully perform their assigned functions; and MANPRINT provides a process for optimizing the relationship between the hardware, software and the human operator and maintainer.

Where RAM and MANPRINT converge is in their application to weapon systems analysis. The sources cited and summarized in this paper represent a growing body of research dedicated to improving the man-machine interface in weapon systems analysis. Lowry and Seaver's work, in particular, provides a step-by-step procedure for relating soldier performance to system performance. Their prescription for measuring system effectiveness combines conventional RAM quantitative techniques with quantitative and qualitative MANPRINT methods to provide a model for evaluating the adequacy of a given system to support current Army soldiers in achieving Army missions successfully.

The importance of integrating RAM and MANPRINT objectives and methodologies is highlighted by two conflicting resourcing trends. First, the Army's modernization program will continue to deploy increasing numbers of technologically advanced items. And, second, resourcing constraints will continue to reduce future manpower and training resources. The implicit risk from these trends is that emerging man-machine systems will not perform within specified constraints. Jesse Orlansky, writing in The All-Volunteer Force After a Decade, sums up the problem as follows:

> "Serious consequences follow if actual human performance is significantly less that that required by the goals set for weapons and support system performance...Another way of saying the same thing is that our weapons and support systems might not perform as required on a battlefield." (Reference 2, p. 169.)

The challenge for the materiel acquisition community is to discover ways to squeeze more and better performance out of diminishing assets. RAM is one way of accomplishing this, and MANPRINT is another, and, together, they offer some powerful tools for honing our competitive edge.

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